

The Demise of the Classical BLR in the Luminous Quasar PG1416–129

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ABSTRACT

New observations of the broad-line quasar PG1416–129 reveal a large decline in its continuum luminosity over the past ten years. In response to the continuum change the “classical” broad component of $H\beta$ has almost completely disappeared (a $\times 10$ decrease in flux). In its place there remains a redshifted/redward asymmetric very broad emission line component. The significance of this change is multifold. (1) It confirms the existence of a distinct redshifted Very Broad Line Region (VBLR) component that persists after the demise of the broad component and that is frequently observed, along with the broad component, in radio-loud sources. (2) The smaller ($\times 2$) intensity change in the $H\beta$ very broad component supports the previously advanced idea that the VBLR is physically distinct and likely to arise in an optically thin region close to the central source. (3) The presence of a strong very broad component in the radio-quiet quasar PG1416–129 reinforces the notion that such “population B” quasars share similar spectroscopic (and hence geometrical and kinematical) properties to radio-loud sources. (4) AGN can show broad, very broad, or both line components simultaneously, making statistical comparisons of source profile widths difficult. (5) The interpretation, in reverberation studies, of the presence or lack of correlated response in broad line wings will be affected by this composite BLR/VBLR structure.

Subject headings: quasars: emission lines — quasars: general — quasars: individual (PG 1416–129) — line: formation — line: profiles

1. Introduction

We present new spectroscopic observations of the radio quiet quasar PG 1416–129 that reveal a significant decrease in optical continuum intensity and the virtual disappearance of the “classical” broad component of $H\beta$ (hereafter indicated as $H\beta_{\text{BC}}$) last observed 10 years ago. There remains

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a strong, very-broad (indicated as $H\beta_{VBC}$) and redshifted component that has declined much less dramatically in response to the continuum change. In §2 we describe the new observations, data reduction procedures and a comparison of the old and new spectra for this source. This is followed (§3) by a discussion of physical and phenomenological implications of the spectra change in PG 1416–129.

2. Observations and Analysis

New spectra of PG 1416–129 ($z=0.12928\pm0.00007$ from [OIII] $\lambda 5007$) were obtained on the 2.12-m telescope of the Osservatorio Astronomico Nacional at San Pedro Martir, Baja California, Mexico on May 9 2000 between 7:28 and 8:32 UT, under photometric sky conditions. A Boller & Chivens spectrograph was equipped with a 600 l/mm grating with a Tektronix TK1024AB CCD chip as the detector (2 arcsec slit width). Suitable standard stars were observed at a similar airmass. The spectrum covers the range $\lambda\lambda 4438 - 6537\text{\AA}$ with an effective spectral resolution of 3.5\AA FWHM. It was reduced with standard IRAF procedures. Line properties were derived after normalization of the two spectra to the [OIII] $\lambda\lambda 4959, 5007$ flux in a spectrum obtained on February 17, 1990 (Boroson & Green 1992: hereafter BG92).

Figure 1 shows the 4200–5500 \AA rest frame region in both the 1990 and 2000 spectra. After subtraction of the underlying continuum (fit with a low order polynomial; contamination from the light of the host galaxy is negligible), the $H\beta$ profiles were cleaned of [OIII] $\lambda\lambda 4959, 5007$, $H\beta_{NC}$, and $HeII\lambda 4686$ emission (for details see Marziani et al. 1996). Observed line flux, rest-frame equivalent width and FWHM values derived from the 2000 May 8 spectrum are given in Table 1. Errors are 20% (2σ) for the flux and equivalent width and 10% (2σ) for the FWHM. $FeII_{opt}$ emission is weak in the 1990 spectrum (BG92 estimated $W(FeII\lambda 4570)=31\text{\AA}$) and weaker in the new spectrum as expected if it correlates with the strength of the classical BLR (e.g. BG92). We subtracted a scaled and broadened I Zw 1 template ($F_\lambda \leq 1 \times 10^{-14}\text{ ergs s}^{-1}\text{cm}^{-2}$) from the 2000 May 8 spectrum in order to remove $FeII_{opt}$ contamination. $HeII\lambda 4686$ emission may have a more significant effect on the blue side of the $H\beta$ profile if a significant $HeII\lambda 4686$ VBC exists in our new spectrum. After several empirical attempts, the smoothest residuals were obtained by using the $H\beta_{VBC}$ measured from our new spectrum as a template to subtract suspected broad $HeII\lambda 4686$ emission. This subtraction assumes a much stronger $HeII\lambda 4686$ emission than the estimate given in BG92 ($W(HeII\lambda 4686)/W(H\beta) \approx 0.04$). The result of a spline fit to $H\beta_{VBC}$ after $HeII\lambda 4686$ subtraction is shown for both spectra in Fig. 2 with parameters detailed in Table 2.

The main observational results of this investigation are: (a) the almost complete disappearance of the $H\beta_{BC}$ (on 2000 May 8 the $H\beta_{BC}$ flux is $\approx \frac{1}{10}$ of the original flux) in a reasonably luminous quasar with bolometric luminosity $\sim 10^{45}\text{ ergs s}^{-1}$ and (b) the much smaller variation in the $H\beta_{VBC}$ component (a factor ≈ 2).

3. Implications

3.1. Implication 1: Existence of a VBLR Associated With $H\beta_{VBC}$

The 1990 observation of the $H\beta$ region in PG 1416–129 showed inflections between narrow ($H\beta_{NC}$), broad and very broad line components. The 2000 spectrum shows the almost complete disappearance of the broad component $H\beta_{BC}$ made more evident by the lack of change in $H\beta_{NC}$. The bulk of the residual broad line emission is associated with the very broad component $H\beta_{VBC}$, also seen in 1990. The robustness of the $H\beta_{VBC}$ component to a dramatic continuum change that quenched $H\beta_{BC}$ strongly suggests that the VBC represents a distinct emitting component. Similar arguments have been made previously based on variability and line inflection evidence (Corbin 1997a,b). The weakness of $FeII_{opt}$ emission in PG 1416–129 suggests that the $H\beta_{VBC}$ cannot be attributed to a red-shelf of enhanced $FeII_{opt}$ emission (Korista 1992). Do all RL and RQ (pop B: with $FWHM(H\beta) \gtrsim 4000 \text{ km s}^{-1}$ see Sulentic et al. 2000a) sources show a VBC? The answer is “no”, at least for a VBC like the one observed in PG 1416–129, within current detection limits. Sources exist with no hint of a BC/VBC inflection, $H\beta$ red wing, or profile shift.

Evidence also exists for VBC components of $HeII\lambda 4686$ (e.g., Ferland Korista & Peterson 1990; Marziani & Sulentic 1993) and $CIV\lambda 1549 \text{ \AA}$ (Laor et al. 1994; 1995) in several sources. It is very likely that these VBC components are related to the $H\beta_{VBC}$, although $HeII\lambda 4686$ may often show a more symmetric, boxy profile (as in PG 1138+222; Marziani & Sulentic 1993). However, even if it is possible to disentangle the $HeII\lambda 4686$ emission from the surrounding $FeII_{opt}$ contamination, it is usually weak, with a flux distributed over a wide wavelength range often merging smoothly with the blue wing of $H\beta$. $HeII\lambda 4686$ asymmetry measurements are therefore intrinsically difficult and dependent on assumptions about the $H\beta_{BC}$ shape even if the s/n of the data is high. Note that the classical BLR of $CIV\lambda 1549$ and other high ionization lines is called VBLR in the ILR/VBLR scheme followed by Brotherton et al. (1994) (see Sulentic & Marziani 1999). In Corbin (1997ab) ILR= our NLR+BLR but VBLR definition is the same. The $CIV\lambda 1549$ VBC that we refer to is redshifted and much broader than the BC in analogy to $H\beta$ (see e.g. Laor et al. 1994, 1995).

3.2. Implication 2: Physics of the BLR and VBLR

BLR The light travel time τ_{LT} for a spherically symmetric BLR is $\tau_{LT} \approx 500 L_{H\beta,42}^{\frac{1}{3}} f_{f,-7}^{-\frac{1}{3}} n_{11}^{\frac{2}{3}}$ days, where $f_{f,-7}$ is the filling factors of the line emitting gas in units of 10^{-7} , $L_{H\beta,42}$ is the $H\beta$ luminosity in units of $10^{42} \text{ ergs s}^{-1}$, and n is the number density in units of 10^{11} cm^{-3} . The $H\beta_{BC}$ luminosity of PG 1416–129 is $L_{H\beta_{BC}} \approx 8 \times 10^{41} \text{ ergs s}^{-1}$ (excluding VBC emission; $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$). The τ_{LT} for the BLR of PG 1416–129 is therefore most likely between several months and a few years. The almost complete disappearance of the $H\beta_{BC}$ in $\lesssim 10 \text{ yr}$ does not pose any fundamental challenge. The simplest scenario is that $H\beta_{BC}$ faded following a high amplitude (a factor $\gtrsim 4$) decrease in ionizing continuum level. The $H\beta_{BC}$ luminosity can be conventionally

explained as due to an ensemble of optically thick clouds of very small filling factor ($f_f \sim 10^{-7}$) in a spherically symmetric region extending from the VBLR radius up to 10^{19} cm.

Another potentially very important constraint arises from the apparent absence of a BC in the $\text{HeII}\lambda 4686$ profile of PG 1411-129. Examination of the PG spectral atlas (BG92) indicates that when a broad component of $\text{HeII}\lambda 4686$ is visible, it is usually broader than $\text{H}\beta_{\text{BC}}$. This is especially true for population B and RL sources (e.g. Corbin & Smith 2000). In PG 1416–129 there is evidence for a $\text{HeII}\lambda 4686_{\text{VBC}}$ but only in our new spectrum where $\text{H}\beta_{\text{BC}}$ has almost disappeared. Negligible $\text{HeII}\lambda 4686$ emission ($I(\text{HeII}\lambda 4686_{\text{BC}})/I(\text{H}\beta_{\text{BC}}) \lesssim 0.03$) implies that the ionization parameter must be very low, $\Gamma \lesssim 10^{-4}$ in the BLR of PG1416–129. This condition is satisfied if the emitting gas is either high density ($n_e \gtrsim 10^{12} \text{ cm}^{-3}$) or located farther away from the continuum source (a condition not supported by the line width and by the variability timescale). If most $\text{HeII}\lambda 4686$ is produced in a VBLR rather than a BLR, the problem of an ionizing photon deficit (Korista et al. 1997) may vanish and we may need to reconsider the formation of the high ionization lines (HIL) in Pop B and RL AGN.

VBLR Several lines of evidence (Corbin 1997a,b; Sulentic et al 2000b) suggest that a very broad line region (VBLR) of optically thin gas exposed to a very strong radiation field is located at the inner edge of the BLR. In the case of PG1416–129 the empirical evidence includes: (1) a difference of 9000 km/s between $\text{FWHM}(\text{BC})$ and $\text{FWHM}(\text{VBC})$ and (2) a much weaker response by the $\text{H}\beta_{\text{VBC}}$ to a large continuum change. In an optically thick medium the intensity of a recombination line is governed by the luminosity of the ionizing continuum. If the medium is optically thin the intensity of the same recombination line is governed by the volume and density of the cloud distribution and is not directly related to the luminosity of the ionizing continuum. The much larger decline of $\text{H}\beta_{\text{BC}}$ with respect to $\text{H}\beta_{\text{VBC}}$ can therefore be explained if $\text{H}\beta_{\text{BC}}$ is emitted in an optically thick medium, while a significant fraction ($\gtrsim 50\%$) of $\text{H}\beta_{\text{VBC}}$ is emitted by optically thin gas (see e.g. Shields et al. 1995).

In the case of PG 1416–129, photoionization calculations performed using CLOUDY 94 (Ferland 2000) are able to reproduce the $\text{H}\beta_{\text{VBC}}$ luminosity assuming that an optically thin screen of gas surrounds the continuum sources at a distance of $10^{17.5}$ cm, with $n_e \sim 10^{11} \text{ cm}^{-3}$, and $\Gamma \gtrsim 10^{-2}$. The $\text{H}\beta_{\text{VBC}}$ is strongly redshifted and redward asymmetric (in PG 1416–129 the peak shift $\Delta v_r \approx 850 \text{ km s}^{-1}$, while the shift at line base is $\Delta v_r \approx 4500 \text{ km s}^{-1}$). If we ascribe the shift to gravitational plus transverse redshift (Corbin 1997b), then it is $\Delta v_r \approx 130 M_{9, \odot} r_{18}^{-1} \text{ km s}^{-1}$, and a black hole mass of a few $10^9 M_{\odot}$ is needed to produce $\Delta v_r \approx 1000 \text{ km s}^{-1}$ at $r \approx 10^{17.5}$ cm.

Any optically thin screen with $\Gamma \gtrsim 0.01$ is expected to be a strong source of $\text{HeII}\lambda 4686$; for $\Gamma \sim 0.1$ $\text{HeII}\lambda 4686$ can become comparable to $\text{H}\beta$. In the case of PG 1416–129 milder conditions seem to be appropriate. We measure an upper limit of $I(\text{HeII}\lambda 4686_{\text{VBC}})/I(\text{H}\beta_{\text{VBC}}) \approx 0.25$ (Table 1), a value close to what has been held for a long time to be the canonical value for type 1 AGN. This is consistent with $\Gamma \approx 10^{-2}$ deduced for the optically thin shell covering all the source needed

to explain the luminosity of $H\beta_{VBC}$.

3.3. Implication 3: An RL – RQ Population B Connection?

We have recently described an Eigenvector 1 parameter space as the optimal discriminator between various AGN broad line classes (Sulentic et al. 2000a,b). Sources with FWHM ($H\beta_{BC}$) $\lesssim 4000 \text{ km s}^{-1}$ (Population A) tend to be RQ while broader lined sources are much more often RL. We identified a RQ Population B that shows line profile and soft X-ray properties indistinguishable from, especially flat spectrum, RL sources. Most of the RL and 26% of the RQ sources in the PG sample (BG92) fall in the population B domain. The various planes of the correlation space show: (1) reasonably strong correlations among pop A sources and (2) little or no correlation among the RL and RQ POP B sources, although their mean values are an extension of the pop A correlations (Sulentic et al. 2000a).

Observational commonalities (and at the same time differences from Pop A) between RL and RQ Pop B sources include: (i) stronger and more frequent optical variability (Ulrich et al. 1997), (ii) more complex/boxy/asymmetric profiles (Sulentic 1989; Eracleous & Halpern 1994; Marziani et al. 1996), (iii) occurrence of double-peaked profiles (e.g. Chen et al. 1989; Sulentic et al. 1995), (iv) occurrence of large single-peaked red/blue line shifts ($\gtrsim 10^3 \text{ km s}^{-1}$) and asymmetries (e.g. Marziani et al. 1993; Gaskell 1983), (v) the absence of a systematic $CIV\lambda 1549$ blueshift (Marziani et al. 1996; Sulentic et al. 2000a), (vi) the absence of a soft X-ray excess (Yuan et al. 1998; Sulentic 2000a) and (vii) the presence of a VBLR emitting component in an uncertain number of sources. All line related comments except (v) refer to the Balmer lines where the phenomenology is better established.

The VBLR property appears to be an important commonality between RL and RQ pop B. Sources like B2 1721-34/PKS1101-32 (Corbin 1997ab), PKS0837-12 (Corbin & Smith 2000), PKS0454-22 (Corbin & Boroson 1996), PKS0214+10 (Eracleous & Halpern 1994), PKS 0403-132/PKS0405-123 (Marziani et al. 1996), 0159-117 (Brotherton 1996) are virtual twins of the 1990 spectrum of PG 1416–129. Detection and accurate measurement of the VBLR feature requires at least moderate resolution ($\lesssim 5\text{\AA}$) and s/n ($\gtrsim 20$ in the continuum near $H\beta$). RQ pop B analogs of PG1416–129 can be found in Marziani et al. (1996) where even relatively FEI_{opt} strong RQ source Fairall 9 shows a VBLR feature. PG1416–129 shows us that pop B RQ sources can have a VBLR as strong as the strongest examples among RL AGN.

The situation is less clear for much FEI_{opt} stronger Population A sources. $H\beta_{BC}$ is in several cases observed to be blue-ward asymmetric, where the stronger blue wing may be associated with a high ionization wind emitting most of $CIV\lambda 1549$ (Marziani et al. 1996; Sulentic et al. 2000ab). The available evidence suggests that RQ Pop A sources lack a VBLR like the one observed in Pop B objects (i.e. redshift $\sim 10^3 \text{ km/s}$ and FWHM $\sim 10^4 \text{ km/s}$). Careful analysis of the $FeII\ \lambda 4570$ -contaminated $HeII\lambda 4686$ line profile would help to clarify the issue.

3.4. Implication 4: Do We Always Measure the Same “BLR” in AGN?

PG1416–129 suggests that the answer to this question is “no”. Sources with “naked” VBLR lines certainly exist. A spectrum of PG1416–129 with lower s/n or resolution would not reveal the small BLR residual as a feature. In 1990 BG92 reported $\text{FWHM}(\text{H}\beta_{\text{BC}}) \approx 6100 \text{ km s}^{-1}$ and $\text{R}_{\text{FeII}} \approx 0.2$ for PG1416. The classical $\text{FWHM}(\text{H}\beta_{\text{BC}})$ was overestimated and R_{FeII} underestimated. This mis-estimation of BLR properties will occur whenever a significant VBC is present unless the local continuum is set above that component. Using the 2000 spectrum to model the VBLR component in the 1990 spectrum (see Fig. 2 and Table 2) suggests that the correct values for the $\text{FWHM}(\text{H}\beta_{\text{BC}})$ and R_{FeII} are 4000 km/s and 0.7 respectively. These parameter changes certainly exceed published error estimates for such measures. In the Eigenvector 1 correlation plane of $\text{FWHM}(\text{H}\beta_{\text{BC}})$ vs. R_{FeII} , this change will move PG 1416–129 towards the population A domain. It will also produce an apparently FeII_{opt} “stronger” source (from $\text{R}_{\text{FeII}} \approx 0.2$ to 0.7) than is typically found for broad line RL/RQ pop B sources.

If we parameterize PG1416–129 today we would measure $\text{FWHM}(\text{H}\beta_{\text{BC}}) \approx 13000 \text{ km s}^{-1}$ along with very weak/undetectable FeII_{opt} . We expect no correlation between those two parameters because we know that FeII_{opt} strength correlates with the classical $\text{H}\beta_{\text{BC}}$ and *not* with the $\text{H}\beta_{\text{VBC}}$. We would in fact be measuring a “naked” VBLR. The implication for statistical studies and sample comparisons is clear: we must take into account the VBLR feature or we are not measuring the same thing in different sources. Sometimes we measure a pure BLR component, sometimes a pure VBLR component and sometimes a composite. The implications for the Eigenvector 1 space are also clear. It is possible that the pop A-B differences motivated by the PG sample reflect the presence of the extra VBLR emitting component in Pop B sources, and that the classical BLR may be more similar from source to source than we have appreciated.

3.5. Implication 5: Inferences from Variability/Reverberation Studies

Much of the predictive power of variability/reverberation studies involves determining the sequential response of the line core and wings. These results have previously been argued to support dominance of radial or rotational motions in the BLR (e.g. Gaskell 1988; O’Brien et al. 1998; Goad et al. 1999). The implication of the VBLR is that the red wing of the line may have nothing to do with the line core. Therefore the presence or lack of a pre-, same or post response allows us to infer nothing about the source structure. Monitoring data for sources like Fairall 9 could now be profitably reprocessed in the light of the VBLR concept.

In a sample of 14 RL sources involved in an annual spectroscopic campaign Corbin & Smith (2000) report that most changes occur in the core of the line rather than the wings. They find that B2 1721-34 shows a decrease in the core component as the continuum declined. They also argue that the wings of the line have increased at the same time. Close examination of their spectra show that most of the change in the wings has occurred on the blue side. All of this is consistent with

the idea that the peak is dominated by the classical BLR which is optically thick. The red wing, especially, arises in large part in optically thin gas, so it would be expected to change much less. In any case the two wings may be phenomenologically distinct.

It is important to stress that AGN Pop A sources mirror the behavior of Pop B and RL AGN. The blue wing of $H\beta$ seems to be associated with an optically thin wind emitting mostly HIL like $CIV\lambda 1549$. The blue wing in population A sources may therefore show a lack of response to continuum change but for reasons unrelated to a VBLR component.

4. Conclusion

The quasar PG1416-129 shows two broad line regions. The classical BLR and VBLR are identified through inflections in the low ionization Balmer line profiles. They have a different place of origin and also arise from a physically distinct (optically thick/thin) regions as indicated by the difference of their response to the continuum change over the past ten years.

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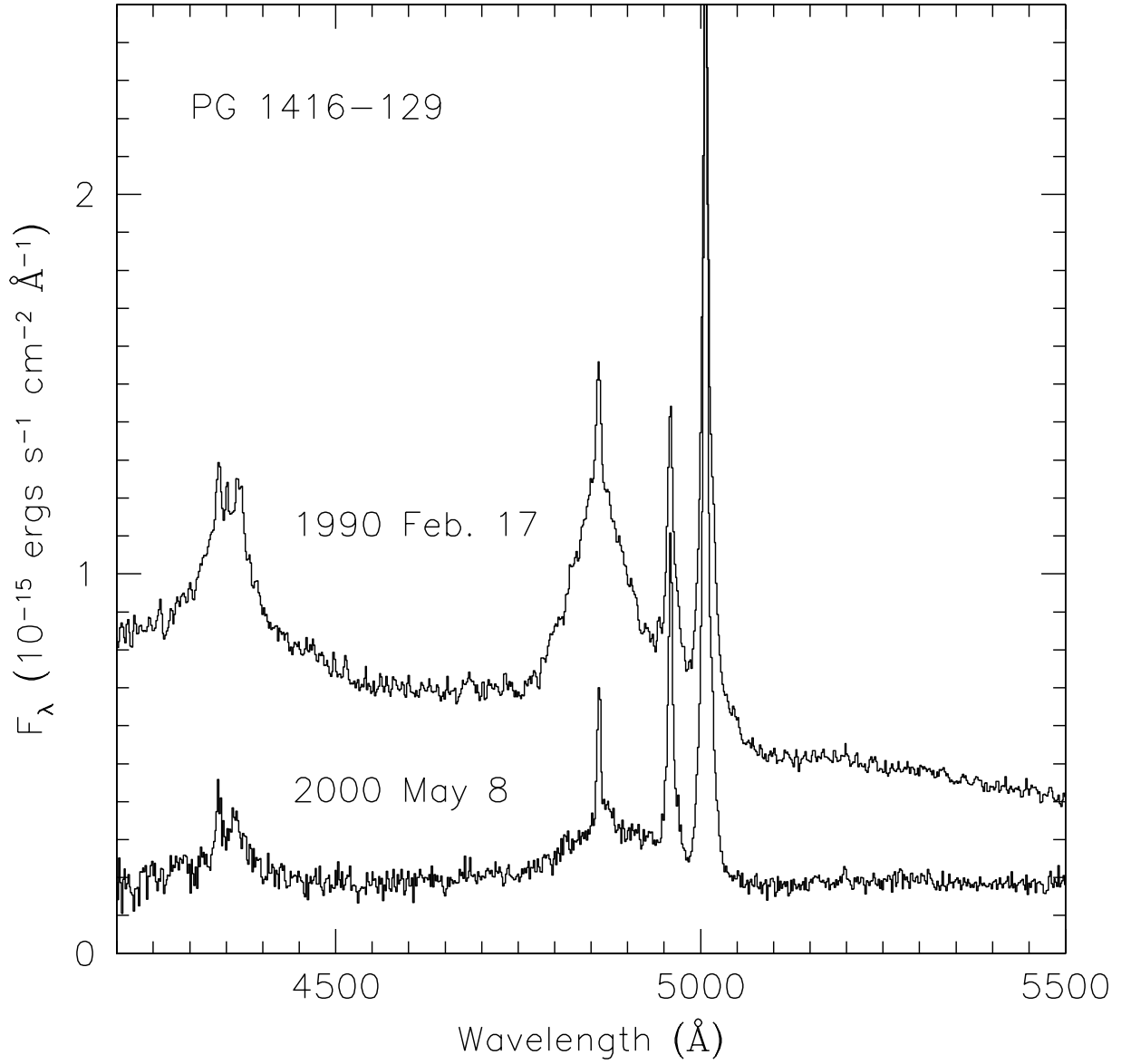


Fig. 1.— Spectra of the $H\beta$ spectral region of PG 1416–129 on Feb. 17, 1990 and on May 8, 2000. Horizontal scale is rest-frame wavelength in Å, vertical scale is observed specific flux (as in BG92). The two spectra have been normalized to the $[OIII]\lambda\lambda 4959, 5007$ flux measured in 1990.

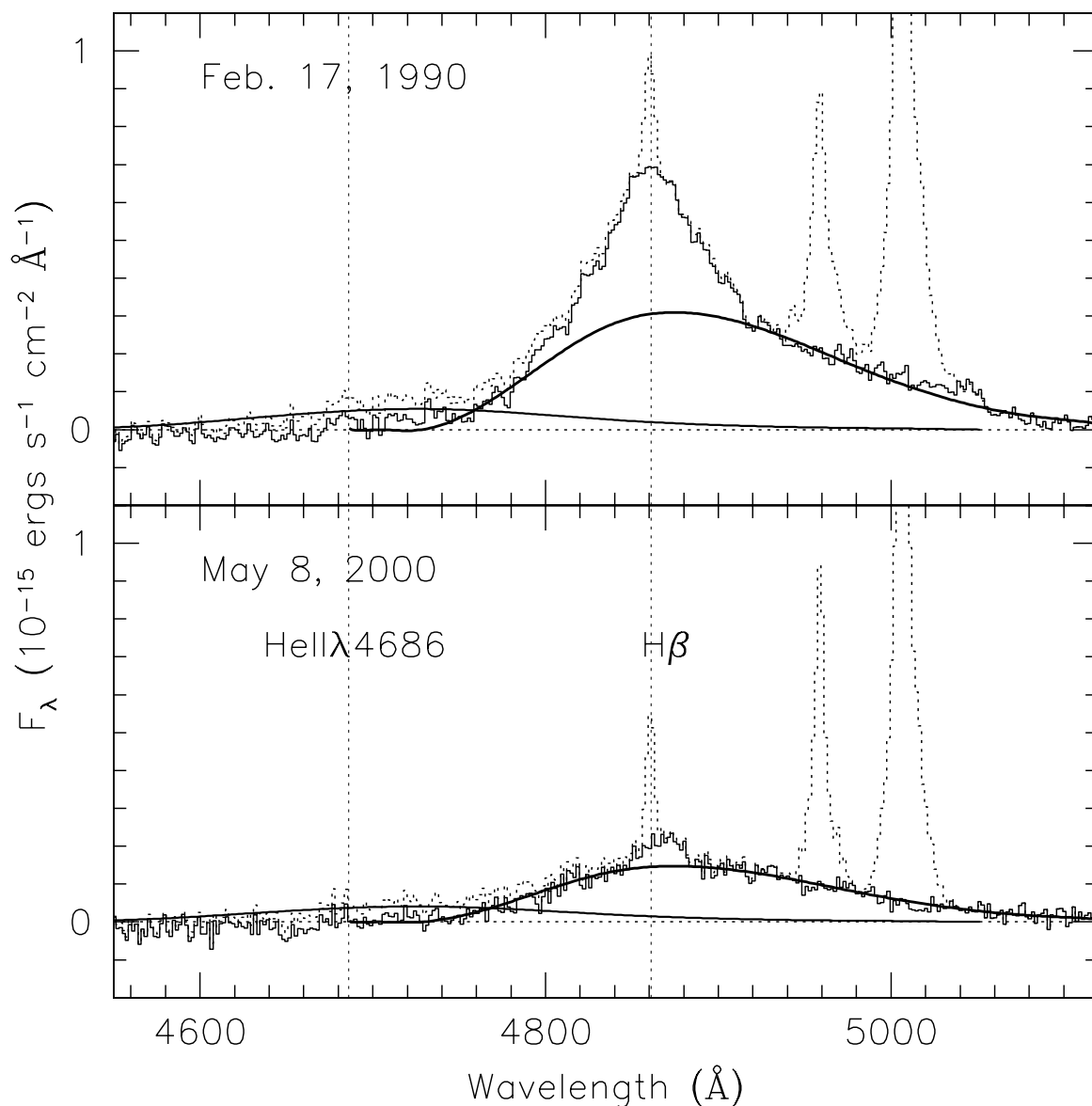


Fig. 2.— Continuum subtracted $H\beta$ line profiles on 1990 Feb. 17 (upper panel) and on 2000 May 8 (lower panel). The dotted line traces the original spectrum after $F_{EII_{opt}}$ subtraction ($F_{EII_{opt}}$ subtraction is however modest and has a negligible effect on the $H\beta$ profile). The solid thin line represents the broad line spectrum, after narrow line and $H EII \lambda 4686$ subtraction. The smooth, thick solid line in the lower panel is the result of a low order spline fitting to the Very Broad Component of $H\beta$; in the upper panel, the fit result on the 2000 May 8 spectrum has been scaled by a factor 2.1 to match the 1990 Feb 17 observation. The $H\beta_{VBC}$ spline fit has been scaled and shifted to account also for the $H EII \lambda 4686$ profile (smooth thin lines).

Table 1. PG 1416–129 Emission Line Spectrum^a

	Flux ^b	W ^c [Å]	FWHM ^d [km s ⁻¹]
H γ _{NC}	1.1 ^e	10: ^e	\lesssim 400 ^e
H γ _{BC+VBC}	11.4: ^f	80: ^f	\gtrsim 4500
[O III] λ 4363	2.2: ^e	20: ^e	1000: ^e
He II λ 4686 _{NC}	0.6: ^g	1.0: ^g	850 ^g
He II λ 4686 _{VBC}	10.0 ^h	75 ^h	14000 ^h
H β _{NC}	2.0	14	250
H β _{BC+VBC}	40.0	300	9000
[O III] λ 4959	9.0	68	370
[O III] λ 5007	27.7	205	370

^aLine parameters measured on the 2000 May 8 spectrum unless otherwise noted, after rescaling to the [O III] λ 4959,5007 fluxes of the 1990 spectrum.

^bObserved, in units of 10^{-15} ergs s⁻¹ cm⁻².

^cRest frame equivalent widths are measured against the bare continuum.

^dCorrected for instrumental profiles assuming $\text{FWHM}_{instr} \approx 7$ Å and 3.5 Å for the 1990 and 2000 spectrum respectively.

^eMeasured after subtraction of a scaled and shifted H β _{BC+VBC} to mimick H γ _{BC+VBC}.

^fMeasured scaling and shifting H β _{BC+VBC}.

^gMeasured on the 1990 Feb. 17 spectrum.

^hMeasured using H β _{VBC} shifted and scaled to 1/4 its original flux.

”:” : uncertainty higher than standard estimate (see text).

Table 2. PG 1416–129 H β Emission Line Variability

Line Identification	1990 Feb. 17 ^a			2000 May 8 ^b		
	Flux	W [Å]	FWHM [km s ⁻¹]	Flux	W [Å]	FWHM [km s ⁻¹]
H β _{BC+VBC}	86.0	160	6000	40.0	300	9000
H β _{BC}	23.0	47	4000	2.0	13	1450
H β _{VBC}	63.0	110	13000	38.0	220	13000

^aSpecific flux at 4500 Å $F_\lambda \approx 7.5 \times 10^{-16}$ ergs s⁻¹ cm⁻² Å⁻¹.

^bSpecific flux at 4500 Å $F_\lambda \approx 1.9 \times 10^{-16}$ ergs s⁻¹ cm⁻² Å⁻¹.